Recent information on Mexico City subsidence

Données récentes sur le tassement de la ville de Mexico

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ABSTRACT: In this paper, updated information about regional subsidence in Mexico City is presented. Topographical data obtained by Gayol in 1891, are compared with the results of recent surveys of the reference points of Sistema de Aguas de la Ciudad de México (SACMEX, 2008) and from the elevations of a cloud of points on the ground surface determined using Light Detection and Ranging (LiDAR) technology. In addition, this paper provides an overview of recent data obtained from systematic studies focused on understanding soil fracturing associated with regional land subsidence and mapping of areas susceptible to cracking in Mexico City Valley.

RÉSUMÉ : Cette communication présente des informations récentes sur le tassement de la ville de Mexico. Les données topographiques de Gayol (1891) sont comparées avec les résultats de levés récents réalisés par Sistema de Aguas de la Ciudad de México (SACMEX, 2008) et avec les élévations d'un nuage de points situés sur la surface du terrain obtenues en utilisant la technique Light Detection and Ranging (LIDAR). Par ailleurs, cette communication présente un panorama des résultats d'études systématiques réalisées dans le but de mieux comprendre la fracturation des sols associée au tassement régional et d'établir une carte de cette fracturation pour la vallée de Mexico.

KEYWORDS: Subsidence, fracturing, cracks, soft clays, surveys

1 INTRODUCTION

Mexico City lacustrine subsoil presents an exceptionally high compressibility and low resistance. Additionally, a regional subsidence phenomenon is affecting the urban area since the early Twentieth Century. One consequence of this phenomenon is the generation of cracks in the soil in many places. More and more frequently, cracks appear in the soil of Mexico City causing alarm among the population and damaging buildings. Both problems, regional subsidence and soil fracturing represent a risk for the stability of buildings and affect the urban infrastructure (Auvinet *et al.* 2017).

The demographic development of Mexico City has created an accelerated demand for services, especially supply of drinking water. One of the cheapest ways to respond to this demand has been the exploitation of the aquifer underneath the urban area by pumping water from deep wells. This activity has induced a regional subsidence phenomenon and the cracking of the soil in the lacustrine and alluvial-lacustrine areas of Mexico City. Due to the high cost of other water supply alternatives, it is expected that extraction of water from the local aquifer will continue for many years.

The regional subsidence in Mexico City has severe consequences. It affects the drainage system, transport infrastructure, foundations of buildings and generates serious risks to the population, since it induces other problems such as flooding of low areas. Therefore, although the regional subsidence is an ancient phenomenon, its study and analysis remain a priority nowadays, inasmuch as it has not been possible to control its basic cause, which frequently leads to adopt emergency solutions.

Therefore, since 2005, the Geocomputing Laboratory group of the Geotechnical Section of Instituto de Ingeniería, UNAM in collaboration with the Mexican Society for Geotechnical Engineering and with the support of municipal authorities has undertaken a systematic study of the phenomenon of soil cracking. The occurrence of cracking may result from any condition that causes important tension stresses in the soil (Auvinet 2008) and the occurrence of cracking has different causes, including contraction of the lacustrine clays by drying, existence of tension stresses associated with buildings weight, hydraulic fracturing in areas of flooding, etc. However, the most important and destructive cracks are a direct consequence of regional subsidence that occurs in Mexico City as a result of pumping water from the aquifer.

2 EFFECTS OF SUBSIDENCE IN FOUNDATIONS AND UNDERGROUND STRUCTURES

Regional subsidence affects foundations as well as underground structures built upon or within the clay deposits of the Valley of Mexico. There are many examples of constructions resting upon pile foundations supported by the first hard layer that are apparently emerging with respect to the surrounding ground surface because of the consolidation of the upper clay formation. As a consequence, the piles are subjected to negative skin friction effects.

The most popular example of the apparent emergence of a structure in Mexico City is the monument built to commemorate de first century of independence of the country in 1910 (Figure 1).

Figure 1. Apparent protruding of the Monument to the Independence (1910-2010).

This case history has been the subject of several comprehensive studies (Ruiz García 1958; Springall 2004; Santoyo *et al*. 2007). Figure 2 shows another striking example of apparent emergence, corresponding to a multistory building (formerly Casa Guardiola) supported by reinforced concrete point-bearing piles, that was designed by Architect Obregón Santacilia in 1942.

Figure 2. Apparent protruding of a building supported by reinforced concrete point-bearing piles.

3 SOIL CRACKING ASSOCIATED TO REGIONAL SUBSIDENCE

The phenomenon of soil cracking is likely to develop as a consequence of any condition imposing large tensile stresses in the soil (Auvinet 2010; Auvinet *et al.* 2013, 2015). However, the most important and destructive cracks come as a direct consequence of regional subsidence sustained by the Valley of Mexico as a result of pumping of water from deep strata.

The regional consolidation process has led to the development of cracks as a consequence of the differential settlements at the sharp transition zones between soft and firm soils, resulting in damages to constructions and public utilities. These cracks are characterized by the presence of steps leading to the zone with the greatest settlement and they are generally parallel to the contours located at the foot of mountain ranges or hills (Figure 3).

After analyzing in detail the mechanism that generates cracks in zones of sharp transition between firm soils and soft lacustrine soils, identification has been made of some particular areas with high potential for cracking such as the transition zones indicated in red color in the pictures shown in Figure 3. Use of microtremors measurements has been proposed to identify zones of potential fissuring in the basin of Mexico (Ovando et al. 2012).

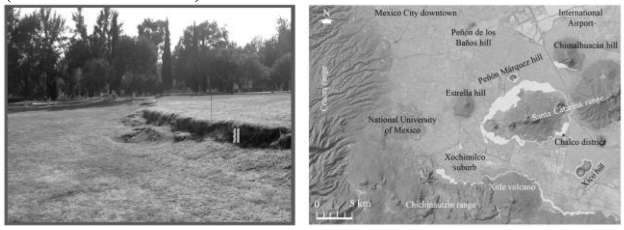

Figure 3. Zone of potential cracking around the foothills of Sierra de Santa Catarina.

4 EVALUATION OF REGIONAL SUBSIDENCE

For purposes of evaluating the subsidence of Mexico City and of the Valley of Mexico use can be made nowadays of the elevation records of more than 3700 benchmarks that are kept and leveled by the following agencies: Sistema de Aguas de la Ciudad de México, Comisión del Agua del Estado de México and Comisión Nacional del Agua.

In addition, huge clouds of points are available from the first surveys ever carried out in the Valley using the LiDAR laser light system with special mention of the survey executed in 2010 by Instituto Nacional de Estadística y Geografía, INEGI (Figure 4).

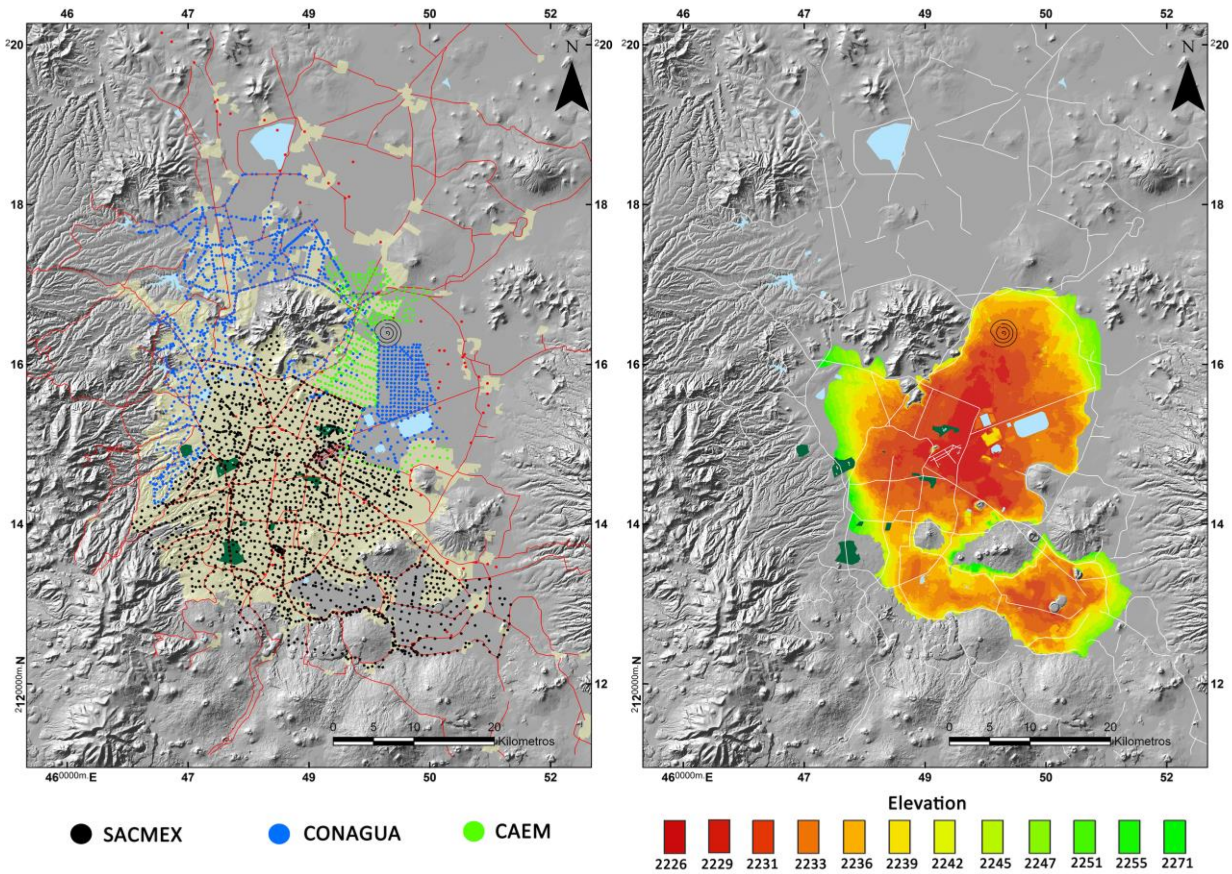

Figure 4. Network of existing benchmarks and results from a LiDAR survey.

Based on the historical data and on the results of systematic leveling surveys performed in Mexico City during more than 100 years, it has been possible to reconstruct the history of the regional subsidence at some points of the downtown area of the City. Figure 5 shows the evolution of subsidence at the Metropolitan Cathedral, Palacio de Minería and Alameda Central park for the 1898-2008 period.

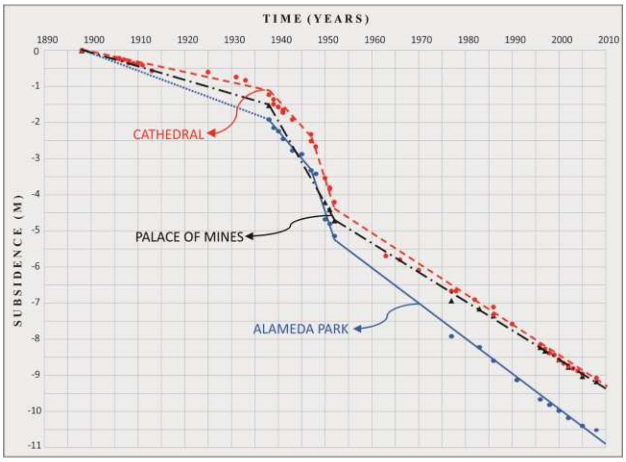

Figure 5. Evolution of regional subsidence at three sites of the Historic Center of Mexico City from 1898 to 2008.

4 .1 *Rates of subsidence in the Valley*

The left side of Figure 6 shows the spatial distribution of the subsidence rate for the 1999–2008 period in the lacustrine zone of the Valley of México (Auvinet et al., 2015a). It can be noticed that the settlement rate is close to 40cm/year at some points. This map could be plotted by combining data supplied by several agencies. Mention should be made that at present the sites with the fastest rates are no longer located in the downtown area of the City but rather at several sites to the east and south of the Valley of Mexico. These sites correspond to the zones where the thickest clay deposits are found in the subsoil. Similar rate values were registered at the end of the 1940 decade of the 20th century, compelling public authorities to impose a ban on new water wells drilled within the boundaries of the old trace of Mexico City for purposes of protecting the existing buildings and the architectural heritage from the undesirable effects of the regional subsidence.

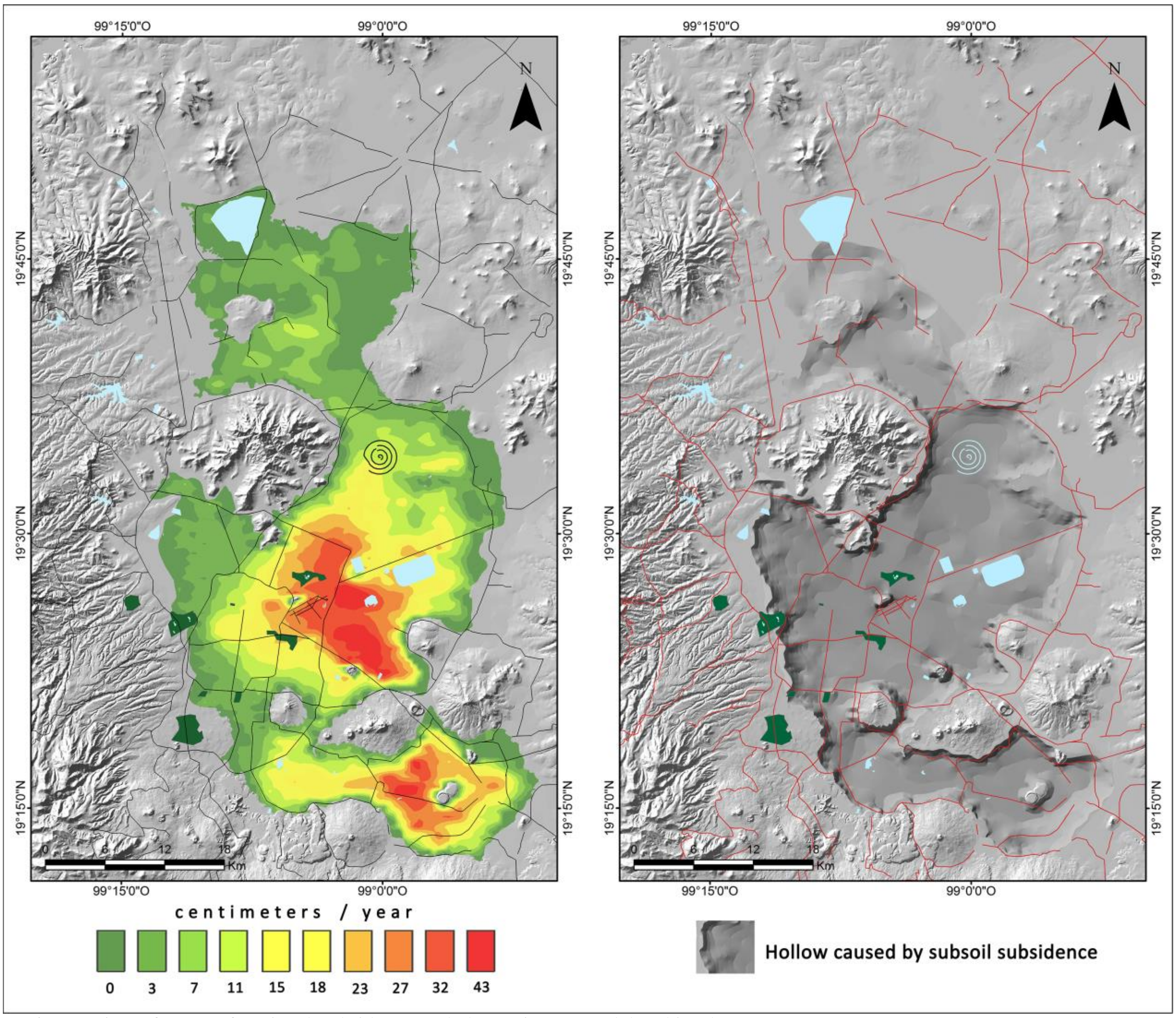

Figure 6. Mapping of rates of regional subsidence and depression created by this phenomenon.

5 NEW MEASURING TECHNIQUES OF THE REGIONAL SUBSIDENCE

Currently, to evaluate the regional subsidence of the Valley of Mexico it is necessary to perform periodic leveling surveys in a network of 3776 benchmarks. The settlement is calculated as the differential elevation in each individual benchmark at different dates.

Indirect methods are now available. They resort to new and very promising technologies to monitor and evaluate the movements of wide areas. These technologies are continuously improved and it is expected that in the short term they will replace the traditional procedures of direct measurements. In the last few years strenuous attempts have been made to evaluate the regional subsidence using indirect methods such as the Global Navigation Satellite System (GNSS), the Laser Imaging Detection and Ranging (LiDAR) system and the Interferometric Synthetic Aperture Radar (InSAR) technology.

6 PERSPECTIVES FOR CONTROL OF SUBSIDENCE AND MITIGATION OF ITS EFFECTS

The control of subsidence demands the implementation of a policy for water supply different from the present one (Tortajada and Castelán 2003). To be able to reduce local pumping it is possible to exploit external or deeper sources (Aguirre 2014), although priority should be assigned to other actions such as the promotion of a more rational use of water and effective control of leaks in the potable water distribution network. Strategies based in the concept of sustainability have been proposed to attain this objective (Calderhead *et al.* 2012; Reséndiz *et al.* 2016). For controlling subsidence it has also been suggested to adopt a pumping strategy such that, in no point of the subsoil, the overconsolidation pressure is exceeded (Larson *et al.* 2001; Reséndiz *et al.* 2016).

Locally, the possibility exists of a partial control of the subsidence effects. For this purpose, in several projects, the injection or extraction of water from the clays of the upper clay formation has been attempted (Pliego 2008). It has also been proposed (Auvinet *et al.* 2016) to resort to the injection of water into the pervious strata interbedded in the aquitard and, in particular, into the so-called "first hard layer". This possibility has been evaluated theoretically (García *et al.* 2012, 2013). The results obtained tend to demonstrate that with reasonable flow rates of water injected in the subsoil it would be possible to protect very important areas such as the Historic Center of Mexico City against the main effects of the regional subsidence. These conclusions should be, however, confirmed by the results of large scale trial injection tests.

Mitigation of the effects of subsidence demands on the other hand the development of increasingly refined methods of design so as to be able to take into account such phenomenon in the design of foundations and in other civil works (Paniagua and Rangel 2009).

9 REFERENCES

Aguirre R. 2014. El pozo profundo de la Ciudad de México, *H2O Gestión del Agua*, Vol. 4, Núm 1, Enero-marzo, Ciudad de México, México.

Auvinet G. 2008. Agrietamiento de suelos, *Proceedings, XXIV Reunión Nacional de Mecánica de Suelos*, special volume, 299–313, Mexico.

Auvinet G. 2010. Soil fracturing induced by land subsidence, *in Land subsidence, Associated Hazards and the Role of Natural Resources Development,* IAHS Publication 339, ISSN 0144-7815: pp. 20-26.

Auvinet G. Méndez E. and Juárez M. 2013. Soil fracturing induced by land subsidence in Mexico City, *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, International Society for Soil Mechanics and Geotechnical Engineering, Paris, France.

Auvinet G., Méndez E. and Juárez M. 2015a. *Sistema de Monitoreo de la Piezometría y de los Hundimientos del Valle de México por extracción de Agua Subterránea* (SIMOH), Informe final de proyecto del Instituto de Ingeniería, UNAM elaborado para la CONAGUA, Ciudad de México, México.

Auvinet G., Méndez E. and Juárez M. 2015b. Evaluation of regional subsidence and soil fracturing in Mexico City Valley, *Proceedings, Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, Buenos Aires, Argentina.

Auvinet G., Méndez E. and Juárez M. 2017. El subsuelo de la Ciudad de México/The subsoil of Mexico City, New edition, Vol. 3, Instituto de Ingeniería, UNAM, Mexico.

Calderhead A.I., Martel R., Garfias J., Rivera A. and Therrien R. 2012. Sustainable Management for Minimizing Land Subsidence of an Over-Pumped Volcanic Aquifer System, *Tools for Policy Design*, Water Resources Management, 26:1847–1864. DOI 10.1007/s11269-012-9990-7.

Carrillo N. 1948. Influence of Artesian Wells on the Sinking of Mexico City, *Proceedings of 2th Congress of International Soil Mechanics and Foundation Engineering*, Vol. VI, 156–159, Rotterdam.

Gayol R. 1891. *Plano General de las atarjeas conforme al proyecto de desagüe y saneamiento de la Ciudad de México*, official map, Mexico.

Instituto Nacional de Estadística, Geografía e Informática (INEGI). 2010. *Data of LiDAR technology in Mexico City*, data bases, Mexico.

Larson K. J., Basagaoglu H. and Marino M. A. 2001. Prediction of optimal safe groundwater yield and land subsidence in the Los Banos-Kettleman City area, California, using a calibrated numerical simulation model, *Journal of Hydrology*, 242(1–2), pp. 79–102.

Ovando E., Lermo J., Auvinet G. and Méndez E. 2012. Microtremors measurements to identify zones of potential fissuring in the basin of Mexico, *Geofísica Internacional*, 2012, 51-2: pp. 143-156.

Paniagua W.I. and Rangel J.L. 2009. *Foundation engineering answers to subsidence problems in Mexico City*, Proceedings, ISSMGE TC36 workshop, Geotechnical engineering in urban areas affected by land subsidence, the cases of Mexico City, Bangkok and other large cities, pp. 131-142. Mexico city, Mexico.

Pliego L. 2008. Control de los efectos de la subsidencia regional mediante extracción e inyección de agua, *Proceedings, ISSMGE TC36 Workshop Geotechnical Engineering in Urban Areas Affected by Land Subsidence*, pp. 117-130, Ciudad de México, México.

Reséndiz D., Auvinet G. and Méndez E. 2016. *Subsidencia de la Ciudad de México: un proceso centenario insostenible*, Publicación en las Series del Instituto de Ingeniería, UNAM, Ciudad de México, México.

Ruiz-García S. 1958. *Monografía de la Columna de la Independencia*, Departamento del D. F., noviembre. Ciudad de México, México.

Santoyo E. 2007. *Historia y actualidad del hundimiento regional de la ciudad de México*, TGC, S.A. de C.V., Ciudad de México, México.

Sistema de Aguas de la Ciudad de México. 2008. *Set of topographic data of Mexico City, from 1977 to 2008*, Mexico.

Springall G. 2004. Estado de la cimentación del Monumento a la Independencia en 1978: Un episodio histórico-geotécnico, *Revista de la Sociedad Mexicana de Mecánica de Suelos*, No. 191, pp. 23-27, Ciudad de México, México.

Téllez-Pizarro A. 1899. *Apuntes acerca de los cimientos de los edificios en la ciudad de México*, Reprinted in the commemorative volumen of the XXV anniversary of the Mexican Society for Soil Mechanics (1982), Mexico.

Tortajada C. and Castelán E. 2003. *Water Management for a Megacity: Mexico City Metropolitan Area*, AMBIO, 32(2):124-129. DOI: http://dx.doi.org/10.1579/0044-7447-32.2.124.